

Research - Kasteran* — Memory Safety in Systems Programming

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Abstract

Memory safety remains one of the most critical challenges in systems programming, with approximately 70% of security vulnerabilities in low-level code stemming from memory corruption errors. This document surveys the evolution of memory safety techniques—from conservative garbage collection to sophisticated linear type systems and borrow checking—and examines their applicability to the Kasteran* programming language. We argue that a hybrid approach combining affine types with region-based memory management offers the strongest safety guarantees without sacrificing the performance characteristics required for systems programming.

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Abstract

Memory safety remains one of the most critical challenges in systems programming, with approximately 70% of security vulnerabilities in low-level code stemming from memory corruption errors. This document surveys the evolution of memory safety techniques—from conservative garbage collection to sophisticated linear type systems and borrow checking—and examines their applicability to the Kasteran* programming language. We argue that a hybrid approach combining affine types with region-based memory management offers the strongest safety guarantees without sacrificing the performance characteristics required for systems programming.

1. Introduction

Memory safety violations—buffer overflows, use-after-free errors, double frees, and null pointer dereferences—have plagued C and C++ programs for decades. The National Vulnerability Database consistently reports that memory corruption bugs account for the majority of critical-severity vulnerabilities in major software projects (Miller 1). While garbage-collected languages eliminate entire classes of these errors, their runtime overhead and unpredictable pause times make them unsuitable for systems programming, operating systems, and real-time applications. Kasteran* aims to bridge this gap through a novel synthesis of compile-time memory safety guarantees and zero-cost abstractions.

2. Historical Background

The quest for memory safety in systems programming began with attempts to retrofit safety onto existing languages. Cyclone introduced region-based memory management and limited pointer

arithmetic to C, demonstrating that many common memory errors could be prevented at compile time with modest programmer annotation (Jim et al. 1). CCured employed a sophisticated pointer analysis to classify pointers into safe categories, requiring no source changes for existing C programs (Necula et al. 1). These projects proved that static analysis could enforce memory safety, but their annotation burden and restricted programming model limited adoption.

The development of garbage collection saw concurrent pioneers—Boehm-Demers-Weiser conservative GC demonstrated that C and C++ could tolerate a moving collector without type information, albeit with performance costs (Boehm and Weiser 1). Modern generational and concurrent collectors in Java and Go achieve sub-millisecond pause times through sophisticated techniques like load barriers and concurrent marking (Detlefs et al. 1). However, GC remains fundamentally at odds with systems programming requirements: predictable allocation, deterministic destruction, and cache-conscious memory layout.

The watershed moment arrived with Rust, which demonstrated that a borrow checker coupled with an affine type system could enforce memory safety at compile time with zero runtime overhead (Matsakis and Klock 1). Rust’s ownership model—where each value has exactly one owner, and references are classified as mutable (exclusive) or immutable (shared)—prevents data races and use-after-free while maintaining full control over memory layout. The key insight is that lifetimes can be checked statically through a system of regions inferred by the compiler (Jung et al. 1).

3. Technical Analysis

Linear types, derived from Girard’s linear logic, enforce that every value is used exactly once (Girard 1). Affine types relax this constraint to “at most once,” allowing values to be discarded. In the context of memory safety, affine types naturally express ownership transfer: when a value is moved, the source location becomes invalid, preventing double-free errors. The type system ensures that no aliased mutable references exist, which precludes iterator invalidation and data races in concurrent contexts.

The borrow checker extends this model with temporary, non-owning references. A borrow is a reference that does not transfer ownership but must obey two rules: (1) at any time, either one mutable reference or any number of immutable references exist, and (2) references must never outlive their referent. Formally, this is encoded as a constraint satisfaction problem over lifetime variables. The Rust compiler employs region inference, originally developed for region-based memory management in Tofte and Talpin’s work, to verify these constraints automatically (Tofte and Talpin 1). The checker uses a combination of subtyping constraints (where `'a: 'b` means lifetime `'a` outlives `'b`) and a variant of Hindley-Milner unification to solve the resulting constraint graph.

Kasteran* extends this model with fractional capabilities, drawn from Boyland’s work on fractional permissions (Boyland 1). Each capability carries a rational number between 0 and 1 representing the degree of write authority. A capability value of 1 grants full read-write access; values in (0,1) grant read-only access; and the sum of all capabilities referencing a given memory location must never exceed 1. This enables fine-grained sharing patterns—such as multiple reader iterators over a data structure—while maintaining the safety guarantees of exclusive mutation.

Region-based memory management provides an orthogonal axis of safety. A region is an arena from which objects are allocated linearly; the entire region can be deallocated at once, guaranteeing that no dangling references escape the region’s scope. Kasteran* uses a variant of the typed regions found in the Cyclone language, where region lifetimes are tracked by the type system (Grossman et

al. 1). Combined with linear types, region allocation achieves the performance of bump allocation while providing strong safety guarantees.

4. Current State of the Art

Modern systems languages have converged on ownership-based memory safety as the preferred approach. Rust’s borrow checker has been formally verified using separation logic, and the RustBelt project has proven that Rust’s type system guarantees type safety and data-race freedom even in the presence of unsafe code (Jung et al. 1). The Rust standard library’s use of `unsafe` blocks is carefully audited, and tools like Miri (an interpreter for Rust’s mid-level IR) detect undefined behavior in unsafe code at runtime (Jung et al. 1).

Vale introduced a different approach: constraint-based memory management using “generational references” that combine a pointer with a generation counter (Vale 1). On each mutation to a memory location, the generation counter is incremented, and existing references are checked against the current generation at runtime. If a reference’s generation does not match, access is prevented. This approach avoids compile-time lifetime complexity while still preventing use-after-free errors, at the cost of small runtime overhead for generation checks.

The Verified Software Toolchain (VST) project at Princeton demonstrates that C programs can be verified end-to-end using separation logic in Coq (Appel et al. 1). The CompCert verified C compiler, while not enforcing memory safety on source programs, provides a formally verified backend that guarantees the compiled code preserves the semantics of the source, eliminating a class of compiler-introduced memory errors (Leroy 1).

5. Relevance to Kasteran*

Kasteran* adopts a layered approach to memory safety. The default compilation mode enforces full memory safety through a combination of linear types, borrow checking, and region-based allocation. Programmers may opt into “unsafe” blocks for performance-critical inner loops, but the compiler tracks the provenance of every unsafe operation and can generate formal verification conditions to be discharged by an external SMT solver. This design mirrors Rust’s philosophy but extends it with runtime-selectable safety guarantees: a program can be compiled in “strict” mode (maximum safety), “performance” mode (minimal runtime checks), or “verified” mode (SMT-assisted proof generation).

The Kasteran* type system unifies linear types with a capability-based permission model. Every pointer carries a capability token that encodes both the access rights and the lifetime of the referent. The capability calculus supports borrowing, splitting (for read-only sharing), and joining (for exclusive access after all shared references expire). This enables patterns that are difficult in Rust, such as concurrent readers with lock-free access to a shared immutable data structure.

6. Future Directions

Several open problems remain in memory-safe systems programming. The integration of automatic memory reclamation with region-based allocation—specifically, the ability to reclaim individual objects within a region without sacrificing the performance of bump allocation—is an active area of research. Perceus, a reference-counting strategy optimized with reuse analysis, shows promise for combining the determinism of reference counting with the throughput of garbage collection (Reinking et al. 1).

Another frontier is the verification of unsafe code. While Rust’s safety guarantees hold for safe code, the `unsafe` keyword creates a trust boundary. Projects like Creusot and Aeneas are developing tools to verify Rust unsafe code automatically by translating Rust’s MIR into a form amenable to deductive verification (Denis et al. 1). Kasteran* plans to integrate similar capabilities natively, using its SMT-backed verification pipeline to check unsafe blocks at compile time.

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